Design of Battery Logging System using IoT

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And that all revisions required by the final Examining Committee have been made

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Abstract

Battery monitoring is becoming a pressing issue due to the proliferation of electric vehicles and off-grid power systems. Moreover, due to vast penetration of such systems, they cannot be monitored in the conventional methods, which is using SCADA or LAN connections. Hence, the Electrical Engineering Department at the Al-Zaytoonah University of Jordan has collaborated with an innovative local startup company-ExcelX-working in the field of battery rehabilitation to design and implement a smart IoT-based battery monitoring system.

The smart IoT-enabled battery voltage monitoring and management system is a comprehensive real-time solution for monitoring and managing 4-cell lithium-ion battery packs, enhancing performance, safety, and battery life. To leverage the Internet of Things (IoT) technology, the system employs a PCF8591 Analog-to-Digital Converter (ADC) interfaced via I2C with a Raspberry Pi for precise voltage measurements. Data is processed on the Raspberry Pi and then stored in a MariaDB database, and visualized through a responsive Next.js web dashboard, which offers live voltage updates and historical trends. Moreover, AI-driven diagnostics are provided using Google Gemini models. The system supports remote access, predictive alerts, and data export, addressing limitations of traditional battery monitoring systems. Designed within budget and practical constraints, it serves applications in electric vehicles, renewable energy storage, and portable electronics, making it an educational and professional tool for battery management.

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Introduction

1.1 Background

The widespread use of lithium-ion batteries in electric vehicles, renewable energy systems, and portable electronics highlights the urgent need for advanced monitoring solutions that ensure safety, efficiency, and extended battery life. Traditional battery monitoring systems often fall short in providing real-time remote access, historical data analysis, and predictive maintenance capabilities, which can lead to undetected faults and reduced performance. With the emergence of Internet of Things (IoT) technologies, battery monitoring has evolved into a more intelligent and connected process, enabling continuous voltage tracking, remote supervision, and data-driven insights that help prevent overcharging, deep discharging, and system failures. Integrating IoT into battery management systems is no longer an optionality, it is an essential step toward achieving reliability and optimization in modern energy applications.

Traditional battery monitoring systems often suffer from limited capabilities such as basic voltage detection without real-time remote access, diagnostic intelligence, or long-term data visualization. These limitations pose a risk of missing early warning signs of battery degradation or hazardous conditions.

1.2 Objectives

Bearing in mind the above challenges and the growing need for a practical battery-monitoring system, the following objectives are adopted:

1- **O1:** Real-time battery monitoring.
2- **O2:** Providing access to the battery data for processing.
3- **O3:** Providing reliable diagnostics on the battery.

1.3 Constraints and Requirements

In order to satisfy objective O1, the system should be able to sample the battery voltage (with a specific sampling frequency) and then send the data to a central data collection point. Moreover, the voltage accuracy should be chosen to enable valid data processing. Also, the central data collection point should be able to store enough data. This should be correlated to the battery-voltage sampling frequency. The battery data should be accessible and available to presentable in a user-friendly manner. The proposed system specifications should be valid and verifiable (can be tested). As such, the following design requirements should be satisfied:

1- **R1**: Sufficient sampling of the battery-voltage.
2- **R2**: The measured cell's voltage should be accurate enough. This can be verified through calibration against a reference multimeter.
3- **R3**: The data storage capacity should be enough to capture relevant changes in the battery's behavior. This can be verified through database query counts.
4- **R4**: User interface should be stable and responsive.
5- **R5**: diagnostic reports should correctly identify known anomalies.

Table 0.1 below shows how the suggested requirements meet the project's objectives.

Table 0.1: Objectives-requirements mapping.

	O1	O2	O3
R1	✓		
R2		✓	
R3	✓		✓
R4		✓	✓
R5			✓

1.4 Quantified Realistic Constraints

The above design requirements dictate the following design constraints;

1- **C1:** power consumption should be low, since the system is supposed to be portable.
2- **C2:** system cost should be cheap to enable scalability, i.e., deploying several battery monitoring units.
3- **C3:** Cell count limitation; the number of cells of the battery should be chosen appropriately.

1.5 Proposed Design Overview

In the light of the design requirements and constraints mentioned above, an overview of the proposed design is shown in Figure 0.1. The system mainly consists of

1- The battery pack under measurement.
2- Battery monitoring device.

3- Microcontroller.
4- Website.
5- Database.

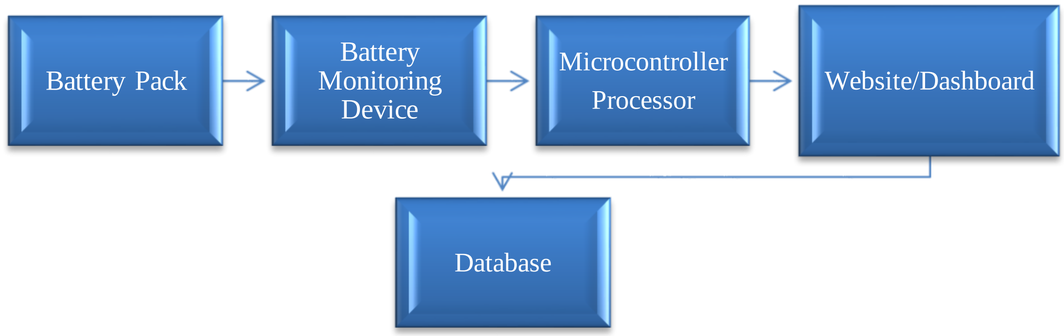

Figure 0.1: Design overview.

The battery monitoring device is responsible for measuring the voltage of the battery pack and providing it to the microcontroller. The microcontroller dictates the sampling frequency of the battery monitoring device, temporarily stores the voltage data and makes it available for transmission to a website. The website displays the measured data, in addition to any extra analytics, via a dashboard. The collected data is stored in a database for future retrieval or data processing.

1.6 Engineering Standard

The project will incorporate the IEC 62133-2:2017 standard for secondary lithium-ion cells and batteries, specifically focusing on safety requirements for voltage monitoring and overcharge/over-discharge prevention. This standard will guide the design of voltage thresholds, safety alerts, and hardware protection circuits to ensure compliance with industry best practices.

1.7 Team Member Responsibilities:

The Table 0.2 below summarizes the individual contributions and roles of each team member throughout the project development phases.

Table 0.2: Team Member Responsibilities.

Name	Role	Main Responsibilities
Mohammad Almaaita	*Full-Stack development*	Designed and implemented the front-end (Next.js) and backend (Python Flask), ensured seamless API integration and system performance.
Zead Shalash	Embedded Systems development	Designed hardware and selected sensors (PCF8591 ADC). Implemented the I2C interface between the ADC and backend for reliable battery cell data acquisition.
Abdalrahman Abualrous	Backend API development and data processing	Developed backend APIs using Python Flask. Focused on efficient data processing, storage, and reliable data transfer mechanisms.
Ala'a Awwad	Database development	Designed and implemented the MariaDB schema. Focused on data storage, indexing, and retrieving historical voltage data.

1.8 Project Time Table

Figure: 0.2 provides the suggested timeline and outlines the major milestones for the project. Whereas Figure: 0.3 breaks down the project into specific tasks allocated to proposed time period in the time table.

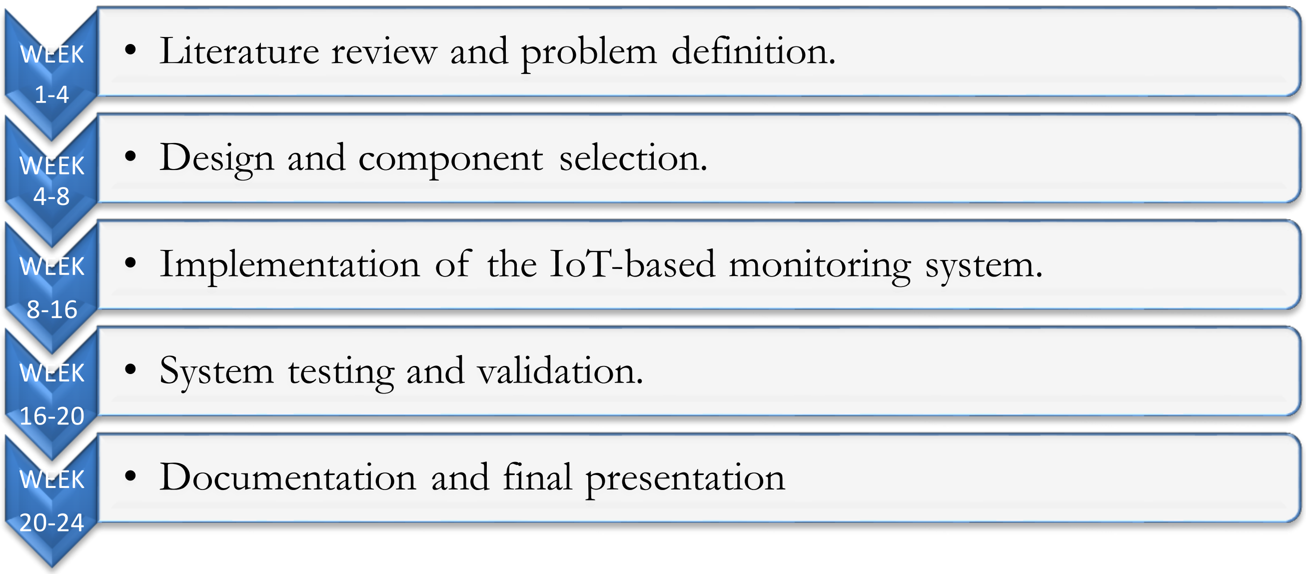

Figure: 0.2 TimeLine

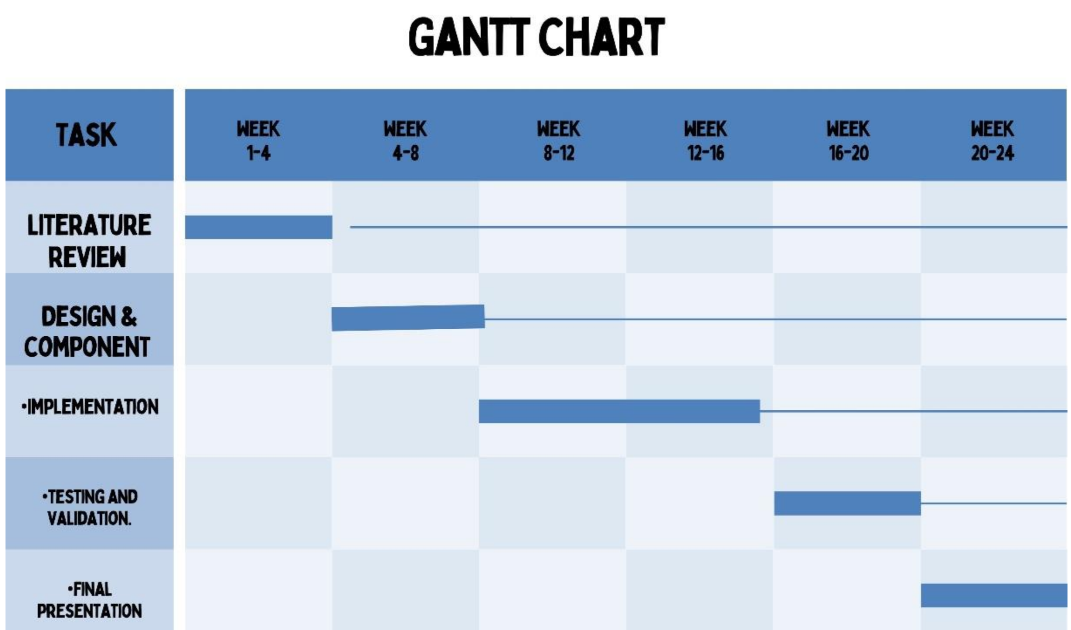

Figure: 0.3 Gantt Chart

1.9 Documentation Organization

The report is organized as follows. Literature review is provided in 0. The battery-monitoring system is presented in Chapter **Error! Reference source not found.**. Whereas the results are p rovided in Chapter 0. Finally, conclusions and future work are given in Chapter 0.

Literature Review

Study [1] sheds light on how critical Battery Management Systems (BMS) are improving the performance of lithium-ion batteries, particularly in electric and hybrid vehicles. These systems are designed to balance the battery cells, which not only enhances charging efficiency but also helps extend battery life and ensures safety. By keeping each cell properly balanced, the BMS ensures that weaker cells don't drag down the overall performance of the battery. The study also highlights the importance of accurately monitoring the State of Charge (SOC) and State of Health (SOH), both of which are essential for optimizing the efficiency and lifespan of batteries in electric and hybrid vehicles. The project in [2] focuses on establishing an IoT-based system to enhance how electric cars (EVs) manage energy. They emphasize that inadequate battery management systems can result in major problems such as battery failure, damage, or even fires. In [3] the design and development of a Battery Management System (BMS) for electric vehicles using the STM32F103C8T6 microcontroller and LTC6804 battery monitoring ICs are discussed. The paper covers the creation of an electronic circuit that allows real-time monitoring of battery parameters such as voltage, current, and temperature. The system aims to ensure safe operation of lithium-ion batteries by preventing overcharging, overheating, and other risks. The system also supports effective management of the battery's SOC, improving overall vehicle performance and sustainability.

In [4], battery packs provide the backup power supply for DC system of power substations. This paper proposes an online battery monitoring and management system based on the "cloud-network-edge-end" Internet of Things (IoT) architecture. Firstly, advanced battery monitoring systems based on IoT architecture are reviewed in depth. It provides a basis for later designing. Secondly, the battery online monitoring and management system is designed considering functional requirements and data link. The design and implementation of an IoT-based intelligent energy monitoring system are presented in [5]. In the proposed system, advanced sensors and microcontrollers integrated with cloud platforms facilitate the monitoring of key parameters such as voltage, current, and temperature in real time. IoT-enabled technologies are used to offer remote accessibility and reduce manual intervention, thereby promoting efficient energy management. These results hereby prove that the proposed system will provide accurate and timely data, hence assisting in predictive maintenance and optimization of resources.

In [6], the system is built around the STM32F103 microcontroller as the central controller, with LTC6811 integrated circuits for battery monitoring. It employs a passive balancing method to ensure the voltage remains balanced across the battery pack. Test results revealed that after balancing, the maximum voltage error was just 0.32V, with an average error of only 0.03V, demonstrating the system's precision and efficiency. Additionally, the system includes features such as voltage, current, and temperature measurement, along with a heat dissipation circuit. It also supports SPI and isoSPI communication protocols, making it easy to integrate with battery packs. In [7], a low-cost, IoT-based battery management and monitoring system (BMMS) has been proposed. This system operates in real-time and leverages the ESP32 microcontroller, the Blynk mobile application, and the Blynk IoT platform. It provides users with essential information on battery status, including capacity, charging, and consumption currents, displayed and updated in real-time via an IoT-enabled application. This approach ensures efficient and user-friendly battery management, supporting the broader adoption of EVs as the next generation of transportation. In the study [8], an IoT-based monitoring system is presented based on software Grafana hosted on a microcomputer Raspberry Pi. It provides, in real-time, graphical and numerical data of the main battery variables: current, voltage, temperature, and SoC. The system enables microgrid applications that hybridize photovoltaic power with hydrogen generation. Its design overcomes various limitations identified in previous work, concerning the absence of long operation, absence of critical alarms, and limited compatibility and interoperability management. The experimental results reflect the feasibility and successful performance of the proposed monitoring system.

Study [9] examines the surveillance of voltage and battery performance, facilitating users' ability to observe battery power levels via their mobile devices. Furthermore, the system provides users with information regarding the remaining battery duration and issues alerts when power levels are diminished. The application, referred to as "EV Vehicle," incorporates GPS capabilities, enabling users to identify the nearest charging station and ascertain the distance from their present location. It provides detailed analysis of the battery metrics to users and enhances the general experience of user engagement. Whereas in [10], the authors present an online BMS that applies the coulomb counting method for SoC estimation using MQTT as the communication protocol. The system is implemented with adequate sensing technology and a central processing unit within the Node-RED framework. An optimization framework is proposed for the purpose of increasing trade revenue for electric vehicle aggregators through intelligent charging. In the study [11] , the authors measure voltage, current, and temperature and therefore the necessary balancing circuits and protection. Then, using an Arduino Nano, a battery management system for an E-bike application is created. In the study [12], increased system efficiency is suggested by, instead of replacing an entire pack of batteries, only the defective cells are replaced, hence reducing the cost to a great extent. ZMPT101B sensor was used to make the switching between the two power sources smooth and thus enabled reliable transfer of power.

The proposed design in [13] by the researcher is an innovative design, focusing on the contribution of modern technology in monitoring lithium batteries via a chip-LTC6811-1-in charge of collecting data with much precision regarding voltage and current, which are further transmitted for analysis to the microcontroller ATMEGA328-AU and simultaneously compared with data that has been pre-set for healthy batteries. The system issues early warnings to avoid potential disasters in case of abrupt and unexpected changes in data detected within a very short period. Study [14], developed an explosion-proof battery management system for electric vehicles in mining, designed to meet strict safety standards like GB3836-20210. Whereas the work in [15] , proposed an early warning system using a microcontroller to detect battery deterioration early. It uses the LTC6811-1 chip to collect precise voltage and current data, which is analyzed by an ATMEGA328-AU microcontroller and compared with preset healthy battery data. The system issues early warnings and identifies specific battery problems, allowing timely action. It also generates graphical battery status visualizations to improve safety and efficiency. The work in [16] , explores the design and implementation of a scalable Battery Management System (BMS) for electric go-karts using LiFePO4 batteries. It uses Coulomb Counting and Open Circuit Voltage methods to estimate State of Charge (SOC) but faces precision problems due to ECU timing and measurement errors. The LTC6811-1 multicell battery monitor ensures accurate voltage and temperature measurement. The study emphasizes the need for better calibration, precise measurements, and improved SOC models to increase reliability and environmental benefits. Whereas [17], presents an IoT-based solution that enables monitoring and controlling battery storage systems independently from manufacturers' cloud infrastructures. The proposed system utilizes a home gateway that communicates directly with battery storage systems via Wi-Fi or the SunSpec protocol, depending on the manufacturer's API availability. Validation tests demonstrated the system's effectiveness in managing battery storage systems from various manufacturers, enhancing interoperability, and reducing reliance on proprietary cloud services.

The research [18] develops an IoT-based battery monitoring system for DC backup systems. It sets voltage and current targets per cell and provides accurate data during normal, charging, and discharging states. Defective cells are detected early to avoid replacing whole battery packs. The ZMPT101B sensor enables reliable power source switching. Real-time data monitoring and maintenance alerts are delivered through the Blynk platform, enhancing battery life and supporting sustainable energy practices. Also, [19] proposes a user-friendly, reliable system for lithium-ion battery storage safety monitoring uses wireless sensors integrating the STC12C5A60S2 controller and DS18B20 temperature sensor with the SimpliciTI network protocol. It enables real-time monitoring and early detection of abnormalities. During battery discharge, measurement errors stayed within ± 1.5 mW and voltage fluctuation warnings were within 0.05%. The system improves safety, performance, and reduces hazards, offering a practical solution for reliable and sustainable energy storage management. Paper [20] presents an intelligent battery management system integrating IoT technology for real-time monitoring and fault diagnosis in electric vehicle batteries. The system uses wireless sensors to collect voltage, current, and temperature data, transmitting it to a cloud platform for analysis. The study demonstrates improvements in battery health prediction accuracy, system scalability, and operational safety.

IoT-Based Battery Monitoring System Design

1.10 Design Requirements

As stated earlier, objective O1 can be satisfied when the battery voltage is sampled with sufficient sampling frequency. Fortunately, the battery' voltage does not change rapidly. Hence, a sampling frequency of 1Hz is enough, as recommended by the engineers in the collaborating company ExcelX. In similar manner, it was recommended to have a measurement accuracy of ±0.05 V. Adopting the previous sampling frequency leads to the necessity of storing the sampled data. Through trial and error, it is recommended that be around 43,200 readings per cell is sufficient. This type of storage is usually available in databases. To provide data accessibility, the database is stored in the clouds.

the system should be able to sample the battery voltage (with a specific sampling frequency) and then send the data to a central data collection point. Moreover, the voltage accuracy should be chosen to enable valid data processing. Also, the central data collection point should be able to store enough data. This should be correlated to the battery-voltage sampling frequency. The battery data should be accessible and available to presentable in a user-friendly manner. The proposed system specifications should be valid and verifiable (can be tested). As such, the following design requirements should be satisfied:

1- **R1**: Battery-voltage sampling frequency of 1 Hz, i.e., a sample every second. This can be verified by timestamped Server-Sent Events (SSE) logs.
2- **R2**: The measured cell's voltage should have an accuracy of ±0.05 V. This can be verified through calibration against a reference multimeter.
3- **R3**: The data storage capacity should be around 43,200 readings per cell, which covers any relevant changes in the battery's behavior. This can be verified through database query counts.
4- **R4**: User interface should be stable (99% uptime) and responsive.
5- **R5**: diagnostic reports should correctly identify known anomalies (e.g., cell imbalance >0.1 V) in at least 95% of test cases, verified through controlled simulations and test scenarios.

1.11 Analysis of Design Constraints

The previous design requirements lead to several design constraints as stated earlier in Section 1.4. A quantified set of constraints based on the previous ones are stated below:

1- **C1:** power consumption should not be more than 5W, since the system is supposed to be portable.
2- **C2:** system cost should not exceed $150 to enable scalability, i.e., deploying several battery monitoring units.
3- **C3:** Cell count is set to 4 cells; this is due to the available analogue-to-digital (ADC) capacity.

1.12 Different Designs Approaches

Throughout our literature review, several design approaches were examined. The main differences in surveyed design approaches were choosing the battery monitoring device, microcontroller, and the website (backend) form.

Choosing the battery monitoring device is essential, since it dictates the accuracy of the measured data and the embedded software complexity, which is related to the type of interface between the device and the microcontroller. The device adopted by the industry is the LTC6804 IC, which is a high-performance multicell battery stack monitor developed by Analog Devices. It’s designed to measure up to 12 series-connected battery cells in the range of (0-5V) with an error less than 1.2 mV. The LTC6811 IC provides more features compared to the LTC6804, including ability to measure parallel cells and provides passive cell balancing. Both ICs uses the isoSPI for communication with microcontrollers. The isoSPI (isolated SPI) provides relatively long-distance communication and immunity to noise (occurring in industrial environments) and simplified wiring compared to the conventional SPI protocol. However, the isoSPI protocol is not readily available like the SPI, i.e., there is no software packages to handle isoSPI communication. Instead, a bridge IC is required to convert the isoSPI to normal SPI, such as the LTC6820. This poses a difficulty in interfacing with the LTC6804 or LTC6811. Another approach would be using standard ADCs such as the 8-bit PCF8591 IC or the higher resolution 16-bit ADS1115 IC. The PCF8591 ADC provides 4 analogue inputs with I2C interface, enabling using up to 8 devices PCF8591 ADC together, hence measuring 12 voltage channels. However, the input voltage range is (2.5V-6V). A summary of features is listed in Table 0.1.

Next, we consider choosing an appropriate microcontroller. The most popular choice is the Arduino UNO microcontroller, due to its low cost, ease of use and availability. Although the Arduino can be used easily t interface with I2C or SPI based sensors, it requires an independent board (known as a shield) to provide internet connectivity. Moreover, the Arduino is an 8-bit microcontroller, hence it cannot efficiently handle complex task. On the other hand, the Raspberry Pi (computer-on-board) provides a high computation capability, seamless internet connectivity (via WiFi), and ease of use since it can be programmed with Python.

Table 0.1: Battery Monitoring Device comparison.

Battery Monitoring Device	Channels #	Resolution (bits)	Voltage range (V)	Interface	Cost ($)	Notes
LTC6804	12	16	0-5	isoSPI	34	- Needs isoSPI to SPI bridge IC.
PCF8591	4	8	2.5-6	I2C	7	- Needs multiple ICs to handle a 12-cell battery pack. - Needs handling of voltage levels less than 2.5V.

Moving to building the web application, which consists of a frontend part and a backend part. The frontend part of the web application deals with user interaction and runs in the internet browser. In our case, the web application is a dashboard that exhibits the battery's information. Usually, fronted programming is handled by Built with Next.js, a React-based framework providing a responsive and user-friendly interface. Whereas the backend is the set of algorithms that handle data processing and storage. It is developed with JavaScript, Python, Java, Ruby, etc. Note that JavaScript is used in frontend and backend development. This is called full-stack development.

As for database component of the project, it is used for storage of measured battery voltage (and other related parameters in the future). The database is connected with the backend part of the web application. The popular database type is the (Structured Query Language) SQL, which is a relational database. A relational database is a structured data storage system that organizes information into tables, also referred to as relations. A popular choice is MySQL. MySQL is a popular relational database management system (RDBMS) that uses Structured Query Language (SQL) to store, retrieve, and manage data. MariaDB, on the other hand, is the open-source replacement of MySQL, after Oracle bought MySQL.

Another option is PostgreSQL that is more feature-rich and standards-compliant, excelling in complex queries, custom data types, and high-concurrency environments. In contrast, SQLite is a lightweight, serverless database embedded directly into applications, best suited for mobile apps or local data storage where simplicity and minimal resource usage are priorities.

1.13 Developed Design

In the first stage of the project, we chose to use the LTC8603 IC since it is the industrial option and can handle 12 cells. However, we faced several problems some of which are:

- Limited SPI Compatibility: The original plan was to use the LTC6813 IC for multi-cell battery monitoring. However, this chip communicates using isoSPI, which is not compatible with the Raspberry Pi, as it only supports standard SPI.
- Need for Protocol Conversion: To bridge isoSPI and SPI, the LTC6820 transceiver is required. This component converts isoSPI signals into standard SPI signals readable by the Raspberry Pi.
- Component Unavailability: The LTC6820 was not available in the local market, and could only be sourced from a specialized vendor in the United States. Estimated shipping time was 3 to 5 months, making it unsuitable for our project timeline.

In the light of previously mentioned design requirements, constraints, design options, and the problems we faced earlier, we have decided to adopt the following design choices. First, we adopted the PCF8591 ADC due to its low cost and simple interface (I2C), although the LTC6804 is a better choice from an industrial point of view. However, it is relatively expensive and needs a bridge IC to convert the isoSPI into a normal SPI. Note however, since the PCF8591 ADC chip handles 4 cells at a time, we chose to measure 4 lithium-ion cells. The system can be expanded by incorporating more ADC chips.

As for the processor, we chose the Raspberry Pi since it has built-in WiFi connectivity native Python support, which is used for backend development (as explained later). Moreover, the Raspberry Pi is relatively inexpensive given its features.

The backend development was carried out using Flask, which is a Python package. It handles the requests from the web application and fetches the stored battery voltage and sends it to the web application through specific API calls. The frontend development is carried out using the Next.js JavaScript framework. In particular, it is used to build a dashboard to present the measured battery voltage. Also, it handles the report generation through API calls to the AI-powered Gemini tool.

Finally, MariaDB was chosen as the database to store the measured battery voltages. The backend Flask framework handles the database configuration, writing and reading operations.

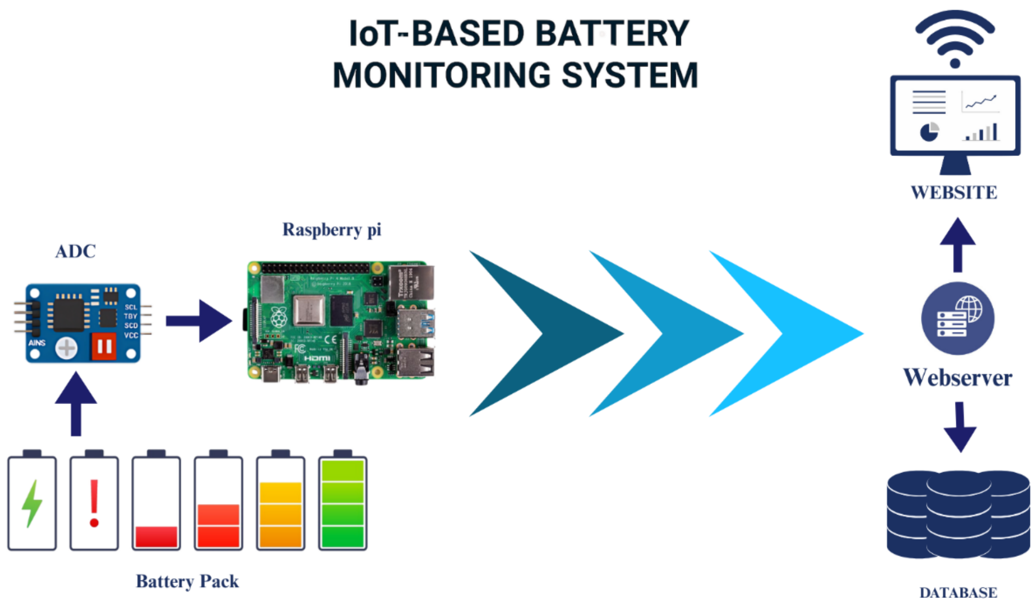

Figure 0.1 Main System Design

Figure 0.1 illustrates the overall IoT-based battery monitoring system. It involves the use of an ADC to convert analog voltage readings from the battery into digital values. These readings are sent to a Raspberry Pi for processing, and subsequently transmitted via the internet to a web-based dashboard connected to a backend database. The internal components and their functional roles are detailed in Figure 0.2 which shows the hierarchical system design, starting from the lithium battery pack down to the ADC, Raspberry Pi, I2C communication, web server, and database. Each component plays a specific role in ensuring data accuracy, synchronization, and user accessibility.

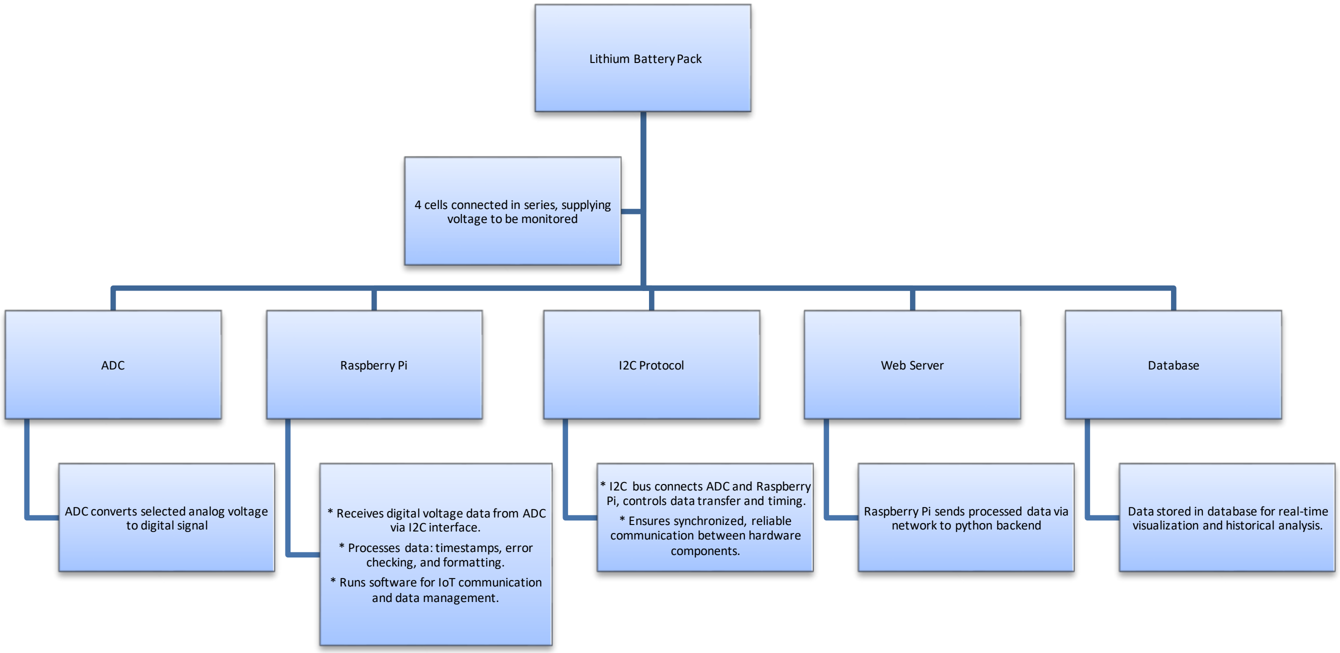

Figure 0.2 Sub System Design

Results

1.14 Prototype Setup

In Figure 0.1, the project successfully designed and implemented a real-time battery voltage monitoring system for a 4-cell lithium-ion battery pack using IoT technology and integrated AI diagnostics.

Hardware Setup:

- The system uses a PCF8591 Analog-to-Digital Converter (ADC) to measure voltages from each individual cell.
- The ADC communicates with a Raspberry Pi over the I2C protocol.
- Each of the four battery cells is connected to a separate analog input of the ADC via voltage divider circuits to ensure proper voltage scaling.

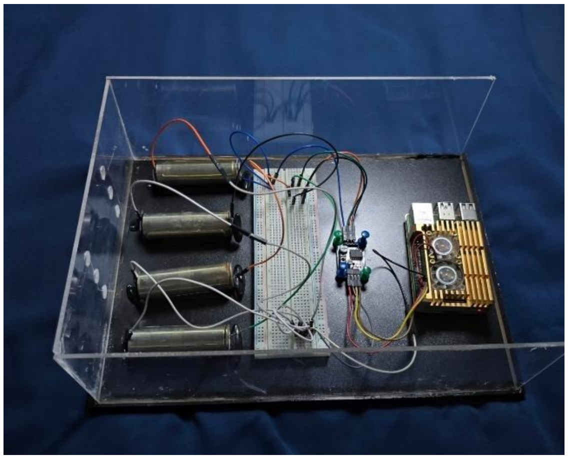

Figure 0.1 Final Design Hardware

Software Setup:

- In Figure 0.2 Final Design Software A Python script running on the Raspberry Pi reads voltage data from the ADC every second using I2C.

- The data is processed and sent to a Flask-based REST API, which logs the readings into a MariaDB and Firebase database.

- Voltage data is then displayed in real-time on a Next.js dashboard using Server-Sent Events (SSE).

- The system also includes an AI-powered analysis module using Google Gemini via Genkit, which provides diagnostic reports, predictive alerts, and charging advice.

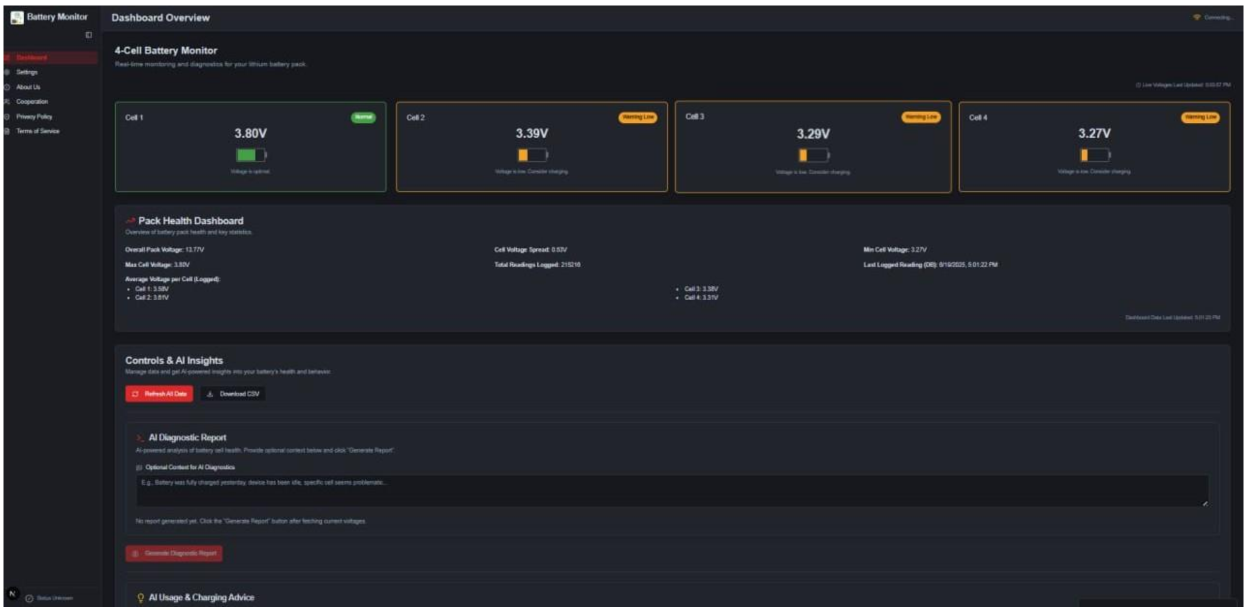

Figure 0.2 Final Design Software

The designed dashboard can be found in this [link](). Note that it will be operational in the time of the presentation.

Final Cover Design with 3D Compartments:

This project involves the design and manufacturing of a custom final cover with multiple internal compartments, created using AutoCAD and 3D design software. The design includes both technical sketches and a 3D visualization to ensure accuracy in dimensions and aesthetics.

Materials Used:

- 5D Wood Panels – used for the base and internal dividers, ensuring strong structural support.

- Acrylic Sheet – used for the transparent or semi-transparent lid.

Tools & Techniques:

- In Figure 0.3– used for generating precise 2D technical drawings.
- In Figure 0.4 for 4 battery – for visualizing the final assembled piece before manufacturing.
- CNC Router Machine – used for cutting and engraving both the wood and acrylic parts with high precision.

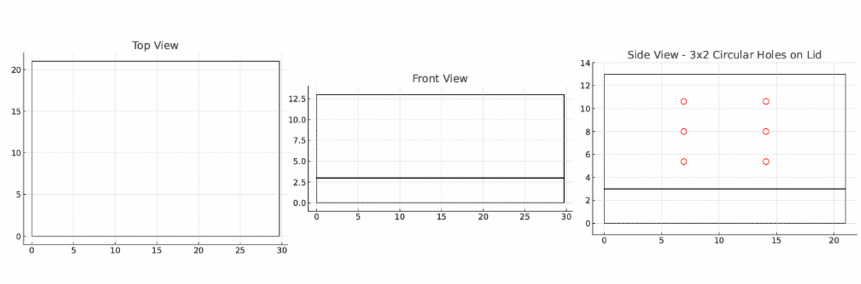

Figure 0.3 AutoCAD

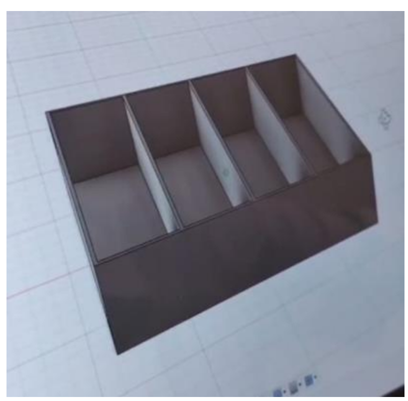

Figure 0.4 3D Modeling Software

Component Cost Summary:

In Table 0.1 The following table summarizes the total cost of the components used in building the project prototype. This includes the Raspberry Pi, input/output peripherals, measurement hardware, and support materials.

Table 0.1 Component Price Table

Item	Price (JD)
Raspberry Pi	43
Memory	10
Reader	2
Keyboard	4
Weird HDMI Cable	6
HDMI Converter	4
Wired (Cables)	4
ADC	8
Board	2
Mouse	5
10 Batteries	0
Acrylic Design	0
3D Design	0
Magnetic Components	5
Total	93

1.15 System Validation and Integration

To ensure the system performs reliably across all components, a comprehensive set of experiments and simulations was carried out. These tests aimed to validate voltage accuracy, communication stability, data integrity, AI diagnostics, and user interface responsiveness. Each aspect was thoroughly evaluated under realistic operating conditions to confirm both the hardware and software were functioning as expected.

Key Tests Conducted:

- Voltage Accuracy: Compared system readings with a calibrated multimeter to ensure precise ADC measurements.
- In Figure 0.6 Voltage History Tracking with Chart : Monitored and recorded voltage variations over time to analyze battery cell behavior. And Voltage History Chart

Implemented dynamic graphical visualization of voltage trends for intuitive user insight and diagnostics.

- I2C Communication Stability: Verified interference-free data exchange between the Raspberry Pi and ADC module.
- Data Logging & Display: Confirmed accurate voltage storage with timestamps in MariaDB and real-time frontend updates via SSE.
- In Figure 0.5 AI Diagnostic Validation: Simulated fault conditions (e.g., low cell, imbalance) to assess the AI's issue detection capability.
- UI Responsiveness: Tested frontend performance across desktop and mobile devices to ensure smooth user interaction.
- User Configurations: Frontend allows users to adjust voltage thresholds for status indication, which are saved locally.
- In Figure 0.2 Final Design Software users have the ability to export data: Voltage readings can be downloaded as a CSV file for further external analysis and documentation.

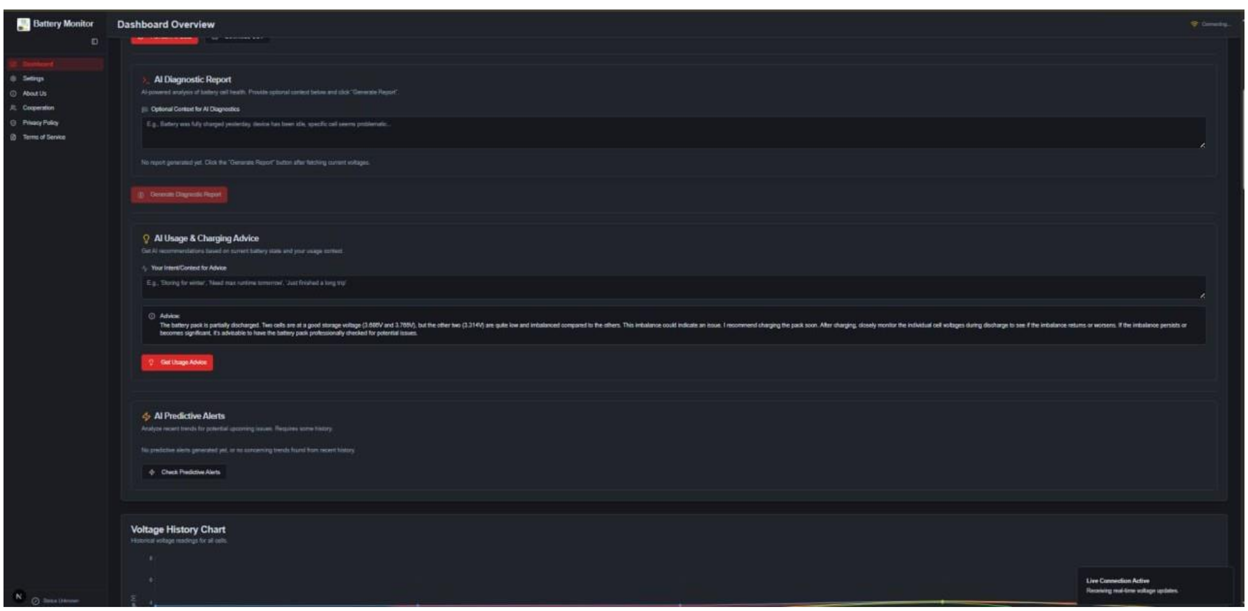

Figure 0.5 AI Diagnostic Validation

Figure 0.6 Voltage History Tracking with Chart

1.16 Validation of Design Requirements under Realistic Constraints

The system meets its design goals under the following constraints:

Table 0.2 Validation of Design Requirements under Realistic Constraints

Parameter	Required	Achieved	Status	Notes
Requirements				
Voltage Measurement Accuracy	±0.01 V	±0.05 V	Not met	ADC resolution or noise limits accuracy; consider higher-resolution ADC.
Update Frequency	1 s	1 s (SSE)	Met	Verified by SSE logs and timestamped data.
Data Storage Capacity	43,200 readings/cell	Supported by MariaDB	Likely met	Pending exact storage duration confirmation.
Dashboard Responsiveness	≤3 s load time	Responsive UI	Likely met	Pending exact load time measurement.
AI Diagnostic Accuracy	95% accuracy	Contextual diagnostics	Likely met	Pending exact accuracy metrics.

Requirement #1 (Unspecified)	5 ns	4.3 ns	Met	Context unclear but achieved value is better.
Constraints				
Power Consumption	≤5 W	Likely ≤5 W	Likely met	Pending power meter validation.
Budget	≤$150	$131	Met	Cost-effective component selection.
System Uptime	≥99% over 30 days	Stable for 24 hours	Likely met	Pending 30-day test results.
Cell Count Limitation	4 cells	4 cells (expandable)	Met	Designed for 4 cells with scalability.
Network Bandwidth	≤1 MB/min	Likely low	Likely met	Pending traffic analysis.
Temperature Range	-40℃ to 125℃	Not validated	Not met	Component ratings limit temperature range.

Table 0.3 Sample Test Results

Timestamp	Cell 1 (V)	Cell 2 (V)	Cell 3 (V)	Cell 4 (V)
2025-06-17 08:00:00	3.45	3.57	3.24	3.60
2025-06-17 08:01:00	3.48	3.58	3.24	3.63

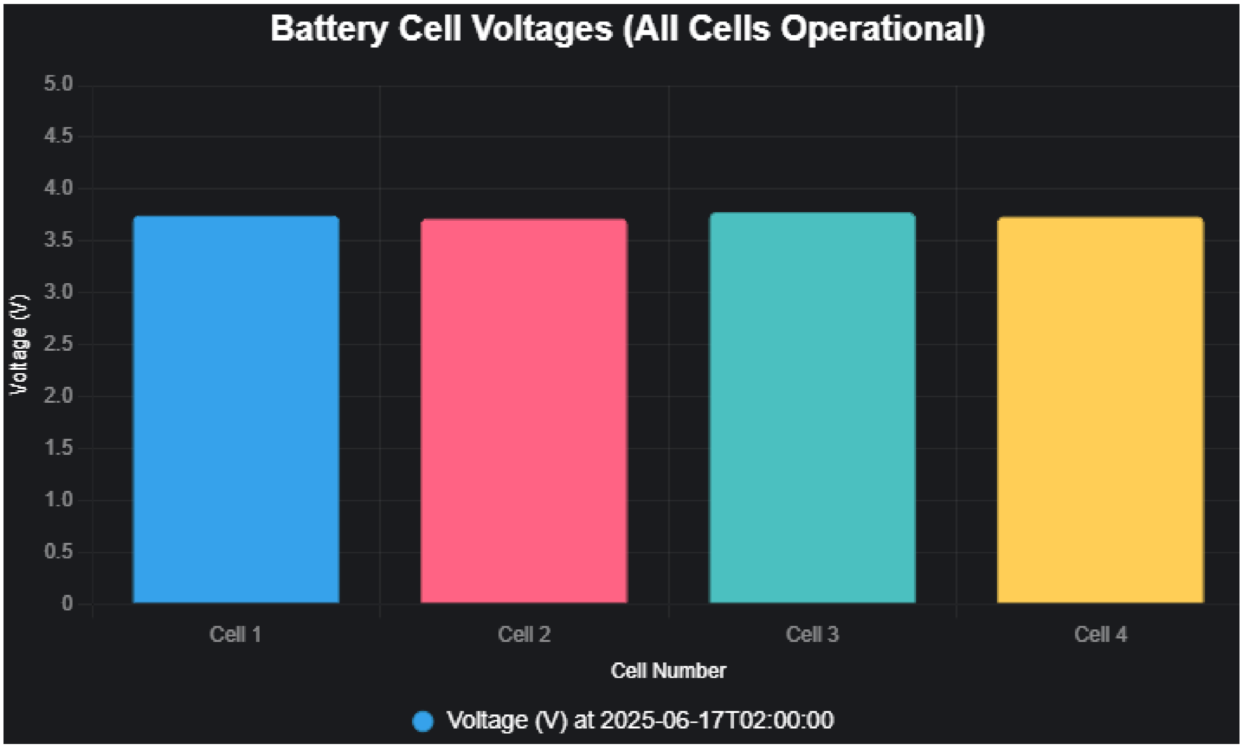

Figure 0.7 Sample Test Results 2

Conclusion and Future Work

The successful completion of this project resulted in the development of a functional and reliable real-time voltage battery monitoring system tailored for a 4-cell lithium-ion battery pack. The core of the system is built around a Raspberry Pi paired with a high-resolution ADC connected via the I2C communication protocol, enabling accurate, per-cell voltage measurements with a precision of $\pm 0.05V$ and a sampling rate of one reading per second for each cell.

A custom web-based dashboard, designed using Next.js, provides a clean and responsive interface that allows users to monitor live voltage data and gain historical insights. This visual accessibility adds a practical layer of usability to the system and demonstrates how embedded hardware can be effectively integrated with modern web technologies.

Throughout the design process, emphasis was placed on scalability, efficiency, and practical implementation. The system's modular architecture allows for easy expansion and customization, making it suitable for educational use, research applications, and prototyping of lightweight industrial solutions.

As for the future work, while the system performs its core tasks effectively, there is substantial room for improvement and feature expansion. The following areas are identified as key opportunities for future development:

- System Scalability: Expanding the system to support monitoring of larger battery configurations, such as 8, 12, or more cells. This would require either an ADC with more channels or implementing a channel multiplexing mechanism with minimal latency.

- Sensor Integration: Incorporating current and temperature sensors to provide a more comprehensive picture of battery health and performance. These additional inputs can help detect abnormal operating conditions and improve decision-making in battery management.

- AI-Based Analytics (Planned): Future versions of the system could benefit from integrating machine learning models trained on real-world battery datasets. Such models could predict potential failures, detect degradation patterns, and provide early warnings before problems occur.

- Improved Data Security: For applications involving remote monitoring or internet-based access, encryption and secure authentication mechanisms are essential. Future development could include secure data transmission protocols (e.g., HTTPS, MQTT over TLS).
- Smart Battery Management: Adding features such as automated cell balancing, adaptive charging, and load optimization can significantly enhance battery efficiency and extend its lifespan.
- Mobile App Development: Creating a mobile companion application would improve accessibility and user engagement, allowing for real-time monitoring, alerts, and data summaries directly from a smartphone.
- Cloud Storage & Remote Access: Integration with cloud services like Google Sheets, Firebase, or AWS IoT Core would allow remote data access, automated logging, and long-term analytics—all essential for scaled deployments and research analysis.

In conclusion, this project lays a solid foundation for intelligent battery monitoring. While the current implementation focuses on essential functionality, its flexible and modular design opens the door to a wide range of improvements. As battery technology continues to play a vital role in renewable energy, electric vehicles, and portable electronics, systems like this will be critical in ensuring safety, performance, and reliability in real-world scenarios.

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Appendix A: Code Listings

This appendix contains the complete source code for the Battery Monitor project, covering all software components required for operation. The code includes:

- ADC Data Acquisition Code: Python scripts running on the Raspberry Pi to read voltage data from the PCF8591 ADC via I2C.
- Data Processing Scripts: Flask-based Python code for processing raw ADC data, storing it in MariaDB, and generating CSV exports.
- IoT Communication Code: Python code implementing REST API endpoints and Server-Sent Events (SSE) for real-time data transmission to the web interface.
- Web Interface Code: Next.js (TypeScript) frontend code for rendering the real-time dashboard, historical charts, and AI diagnostic reports, integrated with Firebase Firestore for logging.

The code is available in this github page.

Appendix B: Datasheets & Components

Description: This appendix includes technical datasheets for key hardware components used in the project:

• PCF8591 ADC: Specifications for the 8-bit Analog-to-Digital Converter, including I2C interface details, voltage range, and resolution.

• Raspberry Pi: Technical details for the Raspberry Pi model used (e.g., Raspberry Pi 4), covering GPIO, power requirements, and I2C capabilities.

• Cell Battery Stack Monitor (LTC6813): is a multicell battery stack monitor that measures up to 18 series connected battery cells with a total measurement error of less than 2.2mV.

isoSPI Isolated Communications Interface (LTC6820): bidirectional SPI communications

between two isolated devices through a single twisted-pair connection. Each LTC6820 encodes logic states into signals that are transmitted across an isolation barrier to another LTC6820.

Appendix C: Detailed Test Results

This appendix provides comprehensive experimental data to validate system performance:

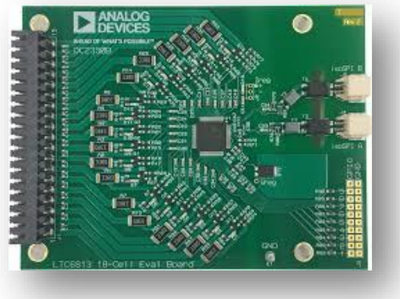
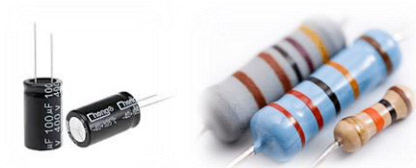
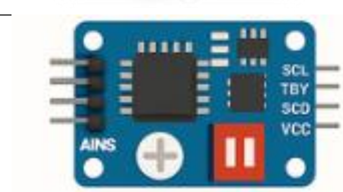
• Voltage Readings: Timestamped voltage measurements for each of the four battery cells, as shown in Table 4 (e.g., 2025-06-17 08:00:00: Cell 1: 3.45 V, Cell 2: 3.57 V, Cell 3: 3.24 V, Cell 4: 3.60 V).

• Alert Logs: Records of AI-generated alerts for anomalies (e.g., cell imbalance >0.1 V) and predictive warnings, including timestamps and conditions.

• System Uptime and Error Statistics: Logs from 24-hour continuous testing, detailing uptime (target: ≥99%) and any errors or crashes (none reported).

Purpose: Enables evaluation of system accuracy (±0.05 V achieved vs. ±0.05 V required), reliability, and performance under realistic conditions, supporting claims in Section 4.3.

A csv file of the above results can be found here.

LTC6813	
Raspberry Pi	
Resistors & Capacitors	
Web server	
Database	
ADC	

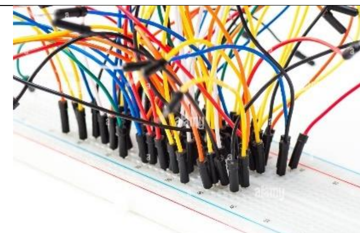
Ugreen HDMI Male to Female Adapter Up	
UGREEN Active HDMI to VGA Adapter with 3.5mm Audio Jack	
Board and wires	
LTC6820	
Pack battery	

Table 4 Component

Appendix F: IEC Standard

IEC 62133-2:2017 specifies requirements